Isotopic differences of soil-plant-atmosphere continuum composition and control factors of different vegetation zones in north slope of Qilian Mountains

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Abstract: Understanding the differences and controlling factors of stable water isotopes in the soil-plant-atmosphere continuum (SPAC) of different vegetation zones is of great guiding significance for revealing hydrological processes and regional water cycle mechanisms. From April 2018 to October 2019, we collected 1,281 samples in the Shiyang River Basin. This study studied the changes of stable water isotopes in the soil-plant-atmosphere continuum (SPAC) of three different vegetation zones (alpine meadow, forest, and arid foothills) in the Shiyang River Basin. The results show that: (1) In SPAC, precipitation isotope has the main controlling effect. From alpine meadows to arid foothills, as the altitude decreases, the temperature effect of precipitation isotopes increases. (2) From the alpine meadow to the arid foothills, the soil water isotope is gradually enriched, indicating that the evaporation is gradually increasing. (3) Alpine meadow plants are mainly supplied by precipitation in the rainy season; forest plants mainly utilize soil water in the dry season and precipitation in the rainy season. The soil water in the arid foothills is mainly recharged by groundwater, and the evaporation and fractionation of plant isotopes are very strong. (4) Temperature and altitude are potential factors that control the isotope composition of SPAC. This research will help understand the SPAC system's water cycle at different altitudes and climates on high mountains.

Keywords: Shiyang River Basin; Stable isotope; Precipitation; Soil water; Plant water

1 Introduction

The relative abundance changes of oxygen and hydrogen isotopes in water technology in water can indicate the water cycle and water use mechanism in plants, so isotope technology has become an increasingly important method for studying the water cycle (Gao et al. 2009; Song et al. 2002; Coplen, 2013; Shou et al. 2013). The stable isotope composition of water is considered to be the "fingerprint" of water, which records a large amount of environmental information that comprehensively reflects the geochemical process of each system and links the composition characteristics of each link (Darling et al., 2003; Raco et al., 2013; Gaj et al., 2014; Nlend et al., 2020). Moreover, it is used to research the analysis of water sources, migration and mixing, and other dynamic processes and played an increasingly important role (White et al., 2013; Bowen et al., 2015). In particular, D and ^{18}O are considered conservative and stable in the absence of high-temperature water-rock interaction and strong evaporation conditions. They are the ideal environmental isotopes for tracing the actual dynamic process of water (William et al., 2013). The application of isotope tracers directly relies on the isotopic labelling of atmospheric vapor or the resulting precipitation (Welker et al., 2000; Konstantin et al., 2008). As an effective tool, stable isotope technology can not only show the relationship between environmental factors and the water cycle (Araguas-Araguas et al., 1998; Christopher et al., 2009), water transport and distribution mechanisms (Gao et al., 2011), and but also deepen the way plants use water (Detjen et al., 2015). And the understanding of the influence of plant characteristics provides a new observation method for revealing the water cycle mechanism in the hydrological ecosystem (Nie et al., 2014; Yu et al., 2007; Wang et al., 2019) and the connection between water use efficiency and water sources (Ehleringe, 1991; Sun et al., 2005; Chao et al., 2019). The research of the water cycle based on SPAC plays a vital role in the study of water in arid areas and the sources of plant water use (Price et al., 2012; Shou et al., 2013). Hydrogen and oxygen stable isotope methods have been used to study the water cycle at the interface of "soil-root", "soil-plant" , and "soil-atmosphere", but only a small number of parameters play an important role in the complex interactions of various surfaces (Durand et al., 2007; Deng et al., 2013; Li et al., 2006; West et al., 2006). At present, the study of stable hydrogen and oxygen isotopes is no longer limited to a single aspect of the SPAC interface water cycle (Zhang et al., 2016; Penna et al., 2020). The tracer study of oxygen isotopes in soil water-plant water-plant fossils in steppe has been carried out internationally, providing a theoretical basis for studying the spatial distribution of oxygen isotopes in soil water and palaeoclimate (Webb et al., 2003). However, the study of the SPAC water cycle as a whole has not been carried out. In future research, the application of hydrogen and oxygen stable isotope technology to the whole system of "five water conversion" of precipitation, surface water, groundwater, soil water and plant water is a new field worth exploring (Wen et al., 2017; Li et al., 2020), which will ultimately solve some core problems in the process of the water cycle and production practice problems. Through research in different water bodies, such as the composition of hydrogen and oxygen isotope, can further understanding the mechanism of vegetation using water in different water bodies of water (Yang et al., 2015), such as the migration and transformation of relations between to solve ecological water requirement for vegetation construction in arid and semiarid areas and some key scientific problems of vegetation restoration and provide a scientific basis for ecological environment construction in western. In the existing research, how to extend the small-scale SPAC water cycle research results to the large-scale area has become a hot spot and difficulty in the current research. Therefore, the application of stable isotope technology provides a new tracer method for the study of the SPAC hydrological cycle (Zhang et al., 2012; Wen et al., 2017; Pan et al., 2020) and the content of SPAC hydrological cycle research has been greatly enriched and expanded (Dawson et al., 2002; Ma et al., 2019).

The stable isotopes of soil water are affected by various factors such as atmospheric precipitation, surface evaporation, soil water migration and vertical movement (Gazi and Feng 2004; Araguas-Aragua et al., 1995; Jennifer et al., 2015). Because the isotope ratio in soil moisture changes with depth, water is transported between plant roots and stems. It reaches the leaves or young unbolted branches before its isotopic composition has not changed (Porporato, 2001; Meissne et al., 2014). Therefore, the content of stable isotopes in soil moisture directly affects the isotopic composition of water in plants xylem (Dawson, 1993; Rothfuss et al., 2017). The source of plant water use can be determined by measuring the δD and $\delta^{18}O$ characteristics of plant xylem moisture and soil moisture at different levels (Wu et al., 2015; Meissner et al., 2014; Yang et al., 2015). Precipitation is an important input factor in the hydrological cycle. The study of the temporal and spatial changes of its isotope characteristics is not only helpful to explore the source of precipitation water vapor and corresponding meteorological and climatic information (Edwards et al., 2010; Daniele et al., 2013; Timsic et al., 2014; Evaristo et al., 2015; Négrel et al., 2016), reflect the historical changes of natural geographic elements (Wei et al., 1994; Speelman et al., 2010; Steinman et al., 2010; Hepp et al., 2015) and climate reconstruction (Thompson et al., 2000; Yao et al., 2008; Xu et al., 2015), but also help to determine the hydraulic connection between water bodies (Yao et al., 2009). Combined with changes in the isotopic composition of surface water, soil water and groundwater, the process of precipitation infiltration and runoff generation can be determined (Bam and Ireso, 2018; Hou et al., 2008) and groundwater recharge and regeneration capacity (Smith et al., 1992; Cortes and Farvolden, 1989). Regional meteorological and hydrological conditions can be determined by comparing different waterline equations and analyzing changes in various water bodies. The contribution of various environmental factors can be evaluated (Hua et al., 2019). Furthermore, it lays a foundation for studying the deep mechanism of the water cycle (Gao et al., 2009). As an important part of the global water cycle, plants control 50-90% of plant evapotranspiration (Jasechko et al., 2013; Coenders-Gerrits et al., 2014; Schlesinger and Jasechko, 2014). Plant roots do not undergo isotopic fractionation when they absorb water (White et al., 1985; Song et al., 2013). Therefore, the water isotope composition of plant roots and stems reflects the isotope composition of water available for plants (Dawson et al., 1991).

The Shiyang River Basin has the greatest ecological pressure and the most severe water shortage in China. Due to the lack of water resources and the small exchange of energy and water with the outside world, the hydrological cycle is mainly based on the vertical circulation of groundwater-soil water-atmospheric water. The purpose of this study is to: (1) analyze the SPAC water cycle process in different vegetation areas; (2) determine the potential factors that control the SPAC water cycle. The research is helping to clarify the water resource utilization mechanism and the local water cycle mechanism of different vegetation areas in high mountainous areas and provide a specific theoretical basis and guiding suggestions for the practical and reasonable use of water resources in arid areas.

2 Materials and methods

2.1 Study area

The Shiyang River Basin is located at the northern foot of the Qilian Mountains, east of the Hexi Region of Gansu Province (Zhu et al., 2018) (Fig. 1). The Shiyang River originates from the snow-capped mountains on the north side of the Lenglongling in the eastern section of the Qilian Mountains. The total length of the river is about 250 km, with a basin area of 4.16×104 km^2. The annual average runoff is about 1.58×10^8 km^3. The river supply comes from meteoric mountain precipitation and alpine ice and snow meltwater. The runoff area is about 1.10×10^4 km^2, and the drought index is 1 to 4 (Zhou et al., 2020). The soil is classified as grey-brown desert soil, aeolian sand soil, salinized soil, and meadow soil. The Shiyang River Basin is located in the hinterland of the mainland. It has a continental temperate arid climate with strong solar radiation. The annual average sunshine hours are 2604.8-3081.8 hours, the annual average temperature is -8.2-10.5℃, the temperature difference between day and night is 25.2℃, the annual average precipitation is 222 mm, and the annual average evaporation is 700-2000 mm. The upper reaches of the basin is an alpine, semi-arid and semi-humid area, with annual precipitation of 400-600 mm, annual evaporation of 700-1200 mm, and an annual average temperature of 0-4℃; the lower reaches of the basin is a warm and arid area with annual precipitation of 200-400 mm, annual evaporation is 1300 - 2000 mm, and the annual average temperature is 4 - 8℃ (Wen et al., 2013). The vegetation coverage in the upper and middle alpine regions is better, with trees, shrubs, and grass covered (Wan et al., 2019). The downstream vegetation coverage is poor under the strong influence of long-term human production and life, mainly desert vegetation.

Fig 1 about here

2.2 Sample collection

Samples of precipitation, groundwater, soil, and plant were collected at Lenglong (alpine meadow), Hulin (forest), and Xiying (arid foothills) in the Shiyang River Basin from April 2018 to October 2019 (Table 1). We sampled 1281 samples in the Shiyang River Basin, including 472 samples from precipitation, 570 samples from soil, 119 samples from plants, and 120 samples from groundwater.

Table 1 about here

Collection of precipitation samples: Collect precipitation with a rain bucket. The rain measuring cylinder is composed of a funnel and a storage part. After each precipitation event, the collected liquid precipitation is immediately devolved to a 100 ml high-density sample bottle. The sample bottle is sealed with a sealing film and stored at low temperature. Simultaneously, the polyethylene bottle sample is labelled with the date and type of precipitation (rain, snow, hail and rain). For the case of multiple precipitation events in one day, multiple sampling is required.

Collection of soil samples: The soil samples are collected with a soil drill at a depth of 100 cm in the soil at intervals of 10 cm. Put part of the soil sample into a 50 ml glass bottle. The mouth of the bottle was sealed with parafilm and transported to the observation station for cryopreservation within 10 hours after sampling. It would be used for the determination of stable isotope data. The rest of the soil sample was placed in a 50 ml aluminum box, and used the drying method to measure the soil moisture content.

Collection of plant samples: Firstly, collect the xylem stem of the plant with a sampling shear. Then peel the bark, and put the stem into a 50 ml glass bottle. Lastly, seal the mouth of the bottle and keep it frozen until the experimental analysis.

Collection of groundwater samples: The groundwater was collected in polyethylene bottles, and the samples were brought back to the refrigerator at the test station for cryogenic preservation within 10 hours.

2.3 Sample treatment

All the water samples collected are tested with a liquid water analyzer (DLT-100, Los Gatos Research Center, USA) in the Northwest Normal University laboratory. Each sample and isotope standard were analyzed by continuous injection six times. To eliminate the memory effect of the analyzer, we discarded the values of the first two injections and we used the average of the last four injections as the final result value. Isotope measurements are given with the symbol "δ" and are expressed as a difference of thousandths relative to Vienna Standard Mean Ocean Water:

$$\delta\ (‰) = \left(\frac{\delta}{\delta_{v-smow}} - 1\right) \times 1000 \tag{1-1}$$

Where, δ is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the collected sample, $\delta_{v\text{-}smow}$ is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the Vienna standard sample.

Due to the existence of methanol and ethnol in plant water samples, it is necessary to modify plant samples' original data. Using different concentrations of pure methanol and ethanol mixed deionized water, combined with Los Gatos' LWIA-spectral pollutant identification instrument V1.0 spectral analysis software, the establishment of δD and $\delta^{18}O$ spectral pollutant correction method, determine methanol (NB) and ethanol (BB) pollution degree (Meng et al., 2012; Liu et al., 2015). The configuration mode of methanol and ethanol solution concentration in the correction process is similar to Meng's relevant experiments (2012). For the broadband metric value NB metric of the methanol calibration result, its logarithm has a significant quadratic curve relationship with ΔδD and $\Delta\delta^{18}O$, and the formulas are respectively,

$$\Delta\delta D = 0.018(\ln NB)^3 + 0.092(\ln NB)^2 + 0.388\ln NB + 0.785(R^2 = 0.991, \ p > 0.0001) \quad (2\text{-}1)$$

$$\Delta\delta D = 0.017(\ln NB)^3 - 0.017(\ln NB)^2 + 0.545\ln NB + 1.356(R^2 = 0.998, \ p < 0.0001) \quad (2\text{-}2)$$

Its broadband measurements for ethanol correction results in BB metric ΔδD and $\Delta\delta^{18}O$ a quadratic curve and linear relationship, respectively, are:

$$\Delta\delta D = -85.67BB + 93.664(R^2 = 0.747, p = 0.026)(BB < 1.2) \quad (2\text{-}3)$$

$$\Delta\delta D = -21.421BB^2 + 39.935BB - 19.089(R^2 = 0.769, p < 0.012) \quad (2\text{-}4)$$

2.4 Data analysis

Since the isotopic data are generally distributed according to the Kolmogorov-Smirnov (KS) test, Pearson correlation is performed to describe the various correlations between different water types (for example, precipitation, soil water, plant water, and groundwater) and the relationship between isotopes in different vegetation zones and control factors. The significance level for all statistical tests was set to the 95% confidence interval. All statistical analyses were performed using SPSS software.

3. Results

3.1 Changes in meteorological parameters over time

Soil samples were placed in a 50 ml aluminium box, and the drying method determined soil moisture content. Meteorological data, including precipitation, relative humidity and temperature, are obtained from a meteorological station in the Shiyang River Basin. Figure 2 shows the changes in daily precipitation, relative humidity, temperature and soil water content (SWC) in the study area from April 2018 to October 2019. During the summer monsoon (April to September), the accumulated precipitation accounted for 90.4% of the total precipitation, and the average daily precipitation on rainy days was 3.98 mm. During the winter monsoon (October to March), the accumulated precipitation accounted for 9.6% of the total precipitation, and the average daily precipitation on rainy days was 0.13 mm. During the summer monsoon, the relative humidity in the Shiyang River Basin was 43.78%, and during the winter monsoon, it was 35.78%. During the observation period, the temperature from -16.2℃ to 32℃, and the average temperature of summer monsoon and winter monsoon were 20.20℃ and -0.69℃, respectively. The average SWC value of 0-100cm soil layer varies from 2.58% to 89.96 %, and the low SWC value usually appears in summer, which is related to the strong evaporation of soil and the strong transpiration of vegetation.

Fig 2 about here

3.2 The relationship between water stable isotopes in different vegetation zones

According to the definition of the global meteoric water line (GMWL) (Craig, 1961), the linear relationship of $\delta^{18}O$ and δD in local precipitation, soil water, plant water, and groundwater is defined as LMWL, SWL, PWL, and GWL, respectively.

As shown in Fig. 3, from April 2018 to October 2019, there are certain differences in the atmospheric waterline equations of different vegetation zones. The LMWL of alpine meadows (7.88), forests (7.82), and arid foothills (7.72) are all smaller than that of GMWL(8.00). This is because the study area is located in northwestern China's arid area, which is weakly affected by the monsoon, the climate is dry, and the isotopes have undergone strong fractionation. The slope of the SWL in the alpine meadow is the largest (6.07), and the slope of the SWL in the forest (5.10) is greater than the slope of the SWL in the arid foothills (3.94). The intercept has the same characteristics, indicating that the arid foothills' soil evaporation is the largest. The degree of soil evaporation in alpine meadows is the smallest. According to the Natural Resources Survey Report of Shiyang River Basin in 2020, the vegetation coverage rate of the alpine meadow is 25.95%, and the vegetation coverage rate of the arid foothills is 8.48%. The vegetation coverage rate of the alpine meadow is higher than that of the arid foothills, with better water retention ability and less evaporation of soil moisture (Wan et al., 2019; Wei et al., 2019). The slope of the PWL in the arid foothills is the largest (2.45), and the slope of the PWL in the alpine meadow (1.90) is greater than that of the forest (1.69).

According to the weighted average of stable isotopes of various water bodies (Table 2), alpine meadows' soil water isotope value is -9.16‰, the most depleted and the closest to the precipitation isotope value (-9.44‰). The average isotopic values of groundwater (-8.84‰) are located between plants (-1.68‰) and precipitation (-9.44‰), indicating that precipitation is the primary source of replenishment for alpine meadows. The precipitation isotope of the forest (-7.50‰) is the most depleted, and the average isotope of groundwater (-8.56‰) is between soil water (-7.01‰) and precipitation (-8.63‰) but close to precipitation, indicating that forest groundwater is replenished by soil water and precipitation. The mean isotopic values of soil water (-8.23‰) in the arid foothills are between precipitation (-7.50‰) and groundwater (-8.88‰) but closer to groundwater, indicating that the soil water in the arid foothills is mainly supplied by groundwater.

Fig 3 about here

Table 2 about here

3.3 Relationship between soil water and plant water in different vegetation zone

For plants in general, water is absorbed by the root system and moves from root to leaf without hydrogen and oxygen isotope fractionation (Zhao et al., 2008; Lin et al., 1993). Therefore, by analyzing the isotopic composition of soil moisture and plant xylem, it is possible to preliminarily determine whether there is an overlap between soil moisture and plant moisture at different depths (Javaux et al., 2016; Dawson et al., 2002; Rothfuss et al., 2017; Tetzlaff et al., 2017; McCole et al., 2007; Zhou et al., 2015; Schwendenmann et al., 2015). Precipitation, surface runoff, and most groundwater are "initial" sources absorbed by plants after converting into soil water. Before being absorbed by plants, soil water may undergo evaporation to produce isotopic enrichment, resulting in an increase in the $\delta^{18}O$ and δD value of soil water (Chen et al., 2014). Therefore, it can be well explained that the surface soil water in Fig. 4 is more enriched than the deep soil water.

According to the study area’s precipitation, the study area is divided into two time periods: dry season (October-April of the following year) and the rainy season (May-September) for analysis (Fig. 4). In the dry season, alpine meadow plants have the highest concentration of water isotopes (-2.84‰). There is no overlap between soil and plant water, indicating that alpine meadow plants do not directly use soil water in the dry season. In the rainy season, the plant water isotope (-6.04‰) and precipitation isotope value (-6.40‰) are close. The surface and deep layers of groundwater and soil water intersect, indicating that plant water in the alpine meadow in the rainy season are mainly supplied by precipitation. Groundwater does not directly use precipitation but rely on soil water for replenishment. In the dry season, due to the low temperature (average temperature of 0.30°C), there is a large amount of melting ice and snow in alpine meadows, abundant precipitation and abundant melting water, and plants do not directly use soil water. As the temperature rises in the rainy season (average temperature 8.72°C), plant water isotopes undergo intense evaporative fractionation, and isotopes are enriched. With the increase of precipitation, the surface runoff increases, and the soil underwater infiltrates the groundwater. Forest plant water intersects with deep soil during the dry season and intersects with the soil surface during the rainy season. This indicates that forest plants mainly use deep soil water during the dry season and shallow soil water during the rainy season. This is related to the lack of rainfall in the dry season and more rainfall in the rainy season. In Fig. 4, in the rainy season, the surface layer of soil water in the arid foothills intersects with plant water, and the surface and deep layers of groundwater intersect with soil water, and precipitation is the most abundant. It shows that the plant water in the arid foothills in the rainy season preferentially uses the surface water of the soil and does not directly use the precipitation. The soil water mainly supplies the groundwater. In the dry season, plant water is most abundant, and the isotopic values of groundwater and soil water are close. It shows that the soil water in the arid foothills is mainly recharged by groundwater in the dry season. According to the natural resources survey report of the Shiyang River Basin, the buried groundwater level in the arid piedmont area is 2.5-15 meters, and the groundwater burial is relatively shallow, making the soil water in the arid foothills mainly recharged by groundwater in the dry season.

Fig 4 about here

4. Discussion

4.1 Variation of soil isotope and SWC between different vegetation zone

The average variation of $\delta^{18}O$ (δD has the same interpretation as $\delta^{18}O$) and SWC in soil water along the vertical soil profile is shown in Fig.5. Along the three vegetation zones of alpine meadow-forest-arid foothills, soil water isotope gradually enriched. The coefficient of variation of the arid foothills is the largest (-0.15). The coefficient of variation of the forest is the smallest (-0.25), indicating that from forest to arid foothills, it tends to be arider in regions, the greater the coefficient of variation, the greater the instability of stable isotope soil water. The soil water isotopes of different vegetation zones showed the same characteristics as the soil depth changed, that is, they were all depleted in May and August and enriched in October.

The soil water content of alpine meadows (average θ of 42.21 %) is higher than that of forests (average θ of 26.98％) and arid foothills (average θ of 17.05％), and the soil water content of alpine meadows increases with the soil depth (from 43.78 ％ to 49.27 ％), while the soil water content of forests decreases with the soil depth (from 26.10％to 25.41％). Compared with forests, plants in alpine meadows have shallower root systems and smaller canopies, so transpiration and water consumption are lower, and soil water content is high (Csilla et al., 2014; Li et al., 2009; Western et al., 1998). On the one hand, with the increase of vegetation restoration, the area of natural grassland in the Shiyang River Basin has increased. Alpine meadows account for the most significant proportion in the Shiyang River Basin, which increases the soil's water retention capacity in the alpine meadows and reduces the amount of soil water evaporation. On the other hand, there is a lot of precipitation in the upper reaches of the Shiyang River. According to Table 1, Lenglong, a representative of alpine meadows, has an average annual precipitation of 595.10 mm, a low temperature, and an average annual temperature of -0.20°C. The lower temperature and higher precipitation also make the soil water evaporation intensity weak in the alpine meadow. The soil moisture content of the alpine meadows (86.95％) and forests (53.45 ％) is the largest in August, while the arid foothills' soil moisture content (11.13 ％) is the smallest in August. This is because the northern foot of the Qilian Mountains is a windward slope. In August, there is much rain, and a lot of precipitation falls on the high-altitude alpine meadows and forests. The arid foothills have little precipitation and low soil water content.

Fig 5 about here

4.2 Control factors of SPAC in different vegetation zones

4.2.1 The influence of temperature on SPAC

$\delta^{18}O$ changes significantly with seasons. As shown in Fig. 6, with the changes in the water cycle of precipitation-soil water-plant water, the $\delta^{18}O$ of forests gradually accumulates, while the soil water isotopes of arid foothills and alpine meadows are the most depleted in summer. In other seasons, along with precipitation-soil water-plant water, $\delta^{18}O$ are gradually enriched. In summer, alpine meadows have a lot of precipitation and large soil water content, but due to low temperature (average temperature in summer is 9.80°C) and low evaporation, the soil water isotope of alpine meadows is relatively depleted in summer. In the arid foothills, in summer, especially in August, although the temperature is relatively high (the average summer temperature is 23.92°C), the soil water content is low, evaporation is weak, and isotopes are relatively depleted. This phenomenon shows that precipitation plays a major control role in the water cycle of precipitation-soil-plants. Previous studies have shown that local factors, especially temperature, mainly control the stable isotope precipitation changes in mid-latitudes (Dai et al., 2020). If the temperature is below 0°C, the air will expand adiabatically, and the water vapor will change adiabatic cooling (Rozanski, 1992). When the temperature is between 0°C and 8°C, the influence of local water vapor circulation is greater. When the temperature is below 8°C, the secondary evaporation under the clouds is very strong (Ma et al., 2019). Therefore, the temperature is divided into three gradients (below 0°C, between 0°C and 8°C and above 8°C) to analyze the relationship between precipitation isotope and temperature. From the alpine meadow to arid foothills, the correlations between temperature and soil are 0.41, 0.30, and 0.19, respectively, and the correlations with plants are 0.24, 0.27, and 0.25, respectively. Compared with precipitation, the temperature effect is not significant. As shown in Table 3, from the alpine meadow to the arid foothills, the temperature effect of the precipitation isotope is enhanced, and there is a significant positive correlation with temperature, and all have passed the significance test. With the increase of temperature, the temperature effect of precipitation isotope in each vegetation area weakens, and the linear relationship decreases. When the temperature is lower than 0°C, the correlation between the isotope of precipitation in the arid foothills and the temperature fails the significance test. The relationship between alpine meadows, forests, arid foothills and temperature are $\delta^{18}O=0.62T-10.84$ ($\delta D=6.03T-69.93$), $\delta^{18}O=1.58T-12.14$ ($\delta D=12.33T-90.24$), and $\delta^{18}O=1.29T-11.78$ ($\delta D=11.22T-79.09$), respectively. When the temperature is between 0°Cand 8°C, as the temperature increases, the temperature effect of precipitation weakens, which may be related to the weakening of the local water cycle and the enrichment of precipitation isotopes when the temperature rises. The relationship between alpine meadows, forests, arid foothills and temperature are $\delta^{18}O$=0.51T-11.41 (δD=3.34T-70.08), $\delta^{18}O$=2.46T-22.84 (δD=21.41T-171.77), and $\delta^{18}O$=2.27T-22.78 (δD=17.31T-167.94), respectively. When the temperature is above 8°C, there is no correlation between the precipitation isotope and the temperature, but the precipitation isotope value is the most enriched, which may be related to the isotope enrichment caused by the secondary evaporation under the cloud.The relationship between alpine meadows, forests, arid foothills and temperature are $\delta^{18}O$=0.48T-10.82(δD=3.00T-65.59), $\delta^{18}O$=0.13T-7.76 (δD=0.72T-46.49), and $\delta^{18}O$=0.27T-10.13 (δD=0.74T-40.03), respectively.

Fig 6 about here

Table 3 about here

4.2.2 The influence of altitude on SPAC

The study area is divided into the rainy season (May-September) and dry season (10-April of the following year), and the relationship between altitude and isotope is analyzed (Fig. 7). The altitude effect of precipitation isotope is stronger than the relationship between soil water isotope and altitude and the relationship between plant water isotope and altitude, but the relationship between plant water δD and altitude in the rainy season is stronger than the relationship between soil water δD and altitude. It shows that in SPAC, precipitation isotope is most affected by altitude, and plant water isotope is least affected by altitude. As the quality of water vapor rises along the hillside, the temperature continues to decrease, and the isotopic values of precipitation continue to be consumed. From the arid foothills to alpine meadows, the elevation rises from 2097m to 3647m. The average values of precipitation isotopes $\delta^{18}O$ and δD changed from -7.33‰ to -9.10‰, and from -48.62‰ to -54.93‰, respectively. The rate of change was -0.11‰$(100m)^{-1}$, -0.41‰$(100m)^{-1}$, In the globally recognized precipitation

$\delta^{18}O$ altitude gradient range, this rate of change is -0.28‰ $(100m)^{-1}$ (Porch and Chamberlain, 2001). The squares of correlation coefficients between $\delta^{18}O$ and δD of rainy season precipitation and altitude are 0.79 and 0.98. The rate of change is -0.12‰$(100m)^{-1}$ and -1.05‰$(100m)^{-1}$, respectively. In the dry season, the correlation coefficient squares of $\delta^{18}O$ and δD with altitude are 0.88 and 0.90, respectively, and the rate of change is -0.18‰$(100m)^{-1}$ and -0.79‰$(100m)^{-1}$, respectively. It can be seen that the altitude effect of precipitation $\delta^{18}O$ is stronger in the dry season (R^2=0.88) than in the rainy season (R^2=0.79), and the altitude effect of precipitation δD is stronger in the rainy season (R^2=0.98) than in the dry season (R^2=0.90). The relationship between soil water isotope and altitude is stronger in the rainy season (R^2=0.26, R^2=0.73) than in the dry season (R^2=0.28, R^2=0.26). The relationship between plant water $\delta^{18}O$ and altitude is stronger in the dry season (R^2=0.11) than in the rainy season (R^2=0.11), and the relationship between plant water δD and altitude in the rainy season (R^2=0.62) is stronger than that in the dry season (R^2=0.56). It can also be seen from the figure that there are anti-elevation shows in some areas, mainly from forests to arid foothills. This may be related to the existence of reservoirs in the arid foothills. Reservoirs may cause the reversal of the local water vapor cycle-the anti-elevation effect. Generally speaking, there is a negative correlation between altitude and SPAC isotope composition. The altitude effect of precipitation isotope is stronger than the relationship between soil water isotope and altitude, and stronger than the relationship between plant water isotope and altitude.

Fig 7 about here

4.2.3 The influence of relative humidity and precipitation on SPAC

To find out the potential factors that control the isotope composition of SPAC in different vegetation zones, we also analyzed the influence of relative humidity and precipitation on the isotope composition of SPAC. It can be seen from Fig. 8 and Table 4 that the greatest impact of relative humidity on the isotope composition of SPAC appears in the arid foothills in the dry season, with a correlation coefficient of 0.38. In the dry season, the square of the correlation coefficient between forest precipitation isotope and relative humidity Although it is 0.78, there is an inverse humidity relationship between the two, which may be related to the lack of precipitation samples in the dry season. The largest impact of precipitation on the isotope composition of SPAC occurs in the arid foothills in the rainy season, and the square of the correlation coefficient is 0.14. It can also be seen from Figure 8 that the influence of relative humidity and precipitation on the isotope composition of SPAC is stronger in the rainy season than in the dry season, and the impact on precipitation isotope is greater than that of plant water isotope and greater than that of soil water isotope. The influence of relative humidity and precipitation on the isotope composition of SPAC in alpine meadows is greater than that of arid foothills, and greater than that of forests. In general, the SPAC isotopic composition of alpine meadows, forests and arid foothills has a weak precipitation effect, and the correlation with relative humidity is also weak.

By comparing the correlation of temperature, altitude, relative humidity and precipitation with SPAC isotope composition in different vegetation zones, we can see that the correlation between temperature and altitude and SPAC isotope composition is stronger than relative humidity and precipitation. Temperature and altitude are potential factors that control the isotope composition of SPAC.

Fig 8 about here

Table 4 about here

5. Conclusion

This paper uses the hydrogen and oxygen isotope method to study the differences and control factors of SPAC in different vegetation zones. Temperature and altitude are the main controlling factors for the isotope composition of SPAC. From alpine meadows to forests to arid foothills, as the altitude decreases, the temperature effect of precipitation isotope increases, and the influence of temperature increases. When the temperature is lower than 0℃, the temperature effect of the vegetation zone is the strongest. As the depth increases, soil water isotopes are gradually depleted. The soil water content of alpine meadows is the largest and increases with the soil depth, while the forest soil water content decreases with the soil depth, and the soil water content of the arid foothills is the least in August. In the rainy season, plants mainly use precipitation, while in the dry season, forest plants mainly use soil water, while alpine meadow plants do not directly use soil water due to the abundant precipitation and meltwater in the growing season. Exposure of the groundwater level in the arid foothills can provide water for plants in the dry season. Because forests and grasslands affect intercepting rainfall, they delay or hinder the formation of surface runoff, and convert part of the surface runoff into soil flow and groundwater, which can provide part of water resources' role for plants. To better understand the water cycle of SPAC at different temperatures and altitudes in high mountain areas, long-term observations of different plants are needed to provide a theoretical basis for the rational and practical use of water resources in arid mountainous areas.

Data Availability

The data that support the findings of this study are openly available in Zhu (2021) at "Data sets of Stable water isotope monitoring network of different water bodies in Shiyang River Basin, a typical arid river in China", Mendeley Data, V1, doi: 10.17632/t87pm4b5dx.1

Author contributation

Guofeng Zhu and Yuwei Liu conceived the idea of the study; Zhuanxia Zhang analyzed the data; Zhigang Sun and Leilei Yong were responsible for field sampling; Liyuan Sang participated in the experiment; Kailiang Zhao participated in the drawing; Yuwei Liu wrote the paper; Liyuan Sang and Lei Wang checked and edited language. All authors discussed the results and revised the manuscript.

Competing interests

The authors declare no competing interests

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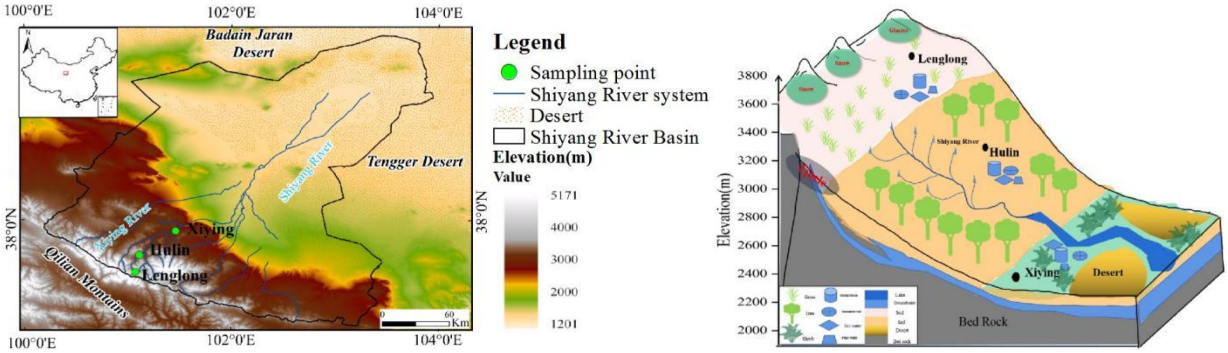

Fig. 1 Study area and observation system

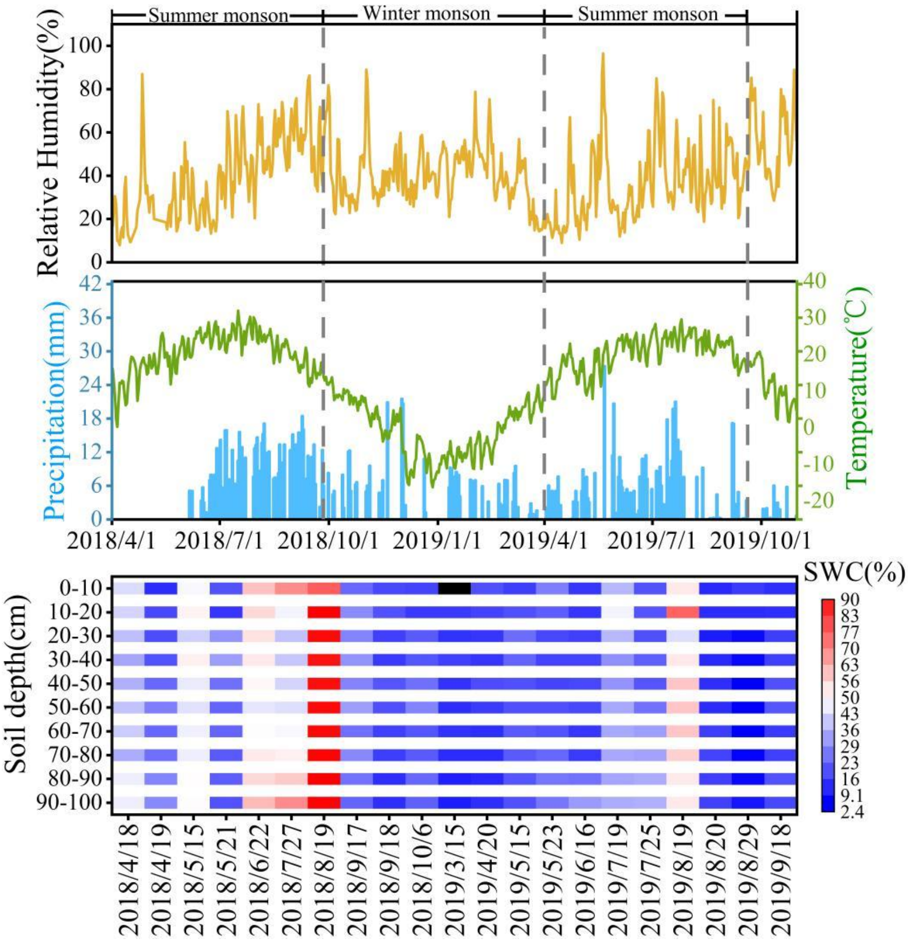

Fig. 2 Diurnal variation of relative humidity, precipitation, temperature, and swc (%) from April 2018 to October 2019

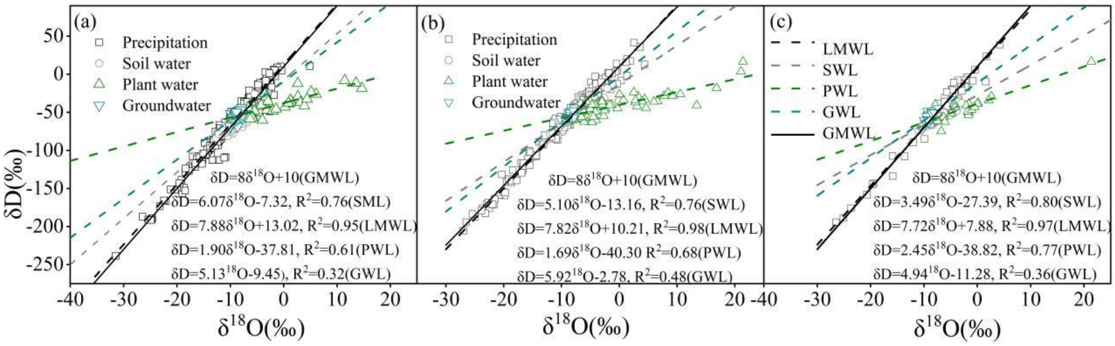

Fig.3 Relationship of stable isotopes in different water bodies in alpine meadow (a), forest (b) and arid foothills (c)

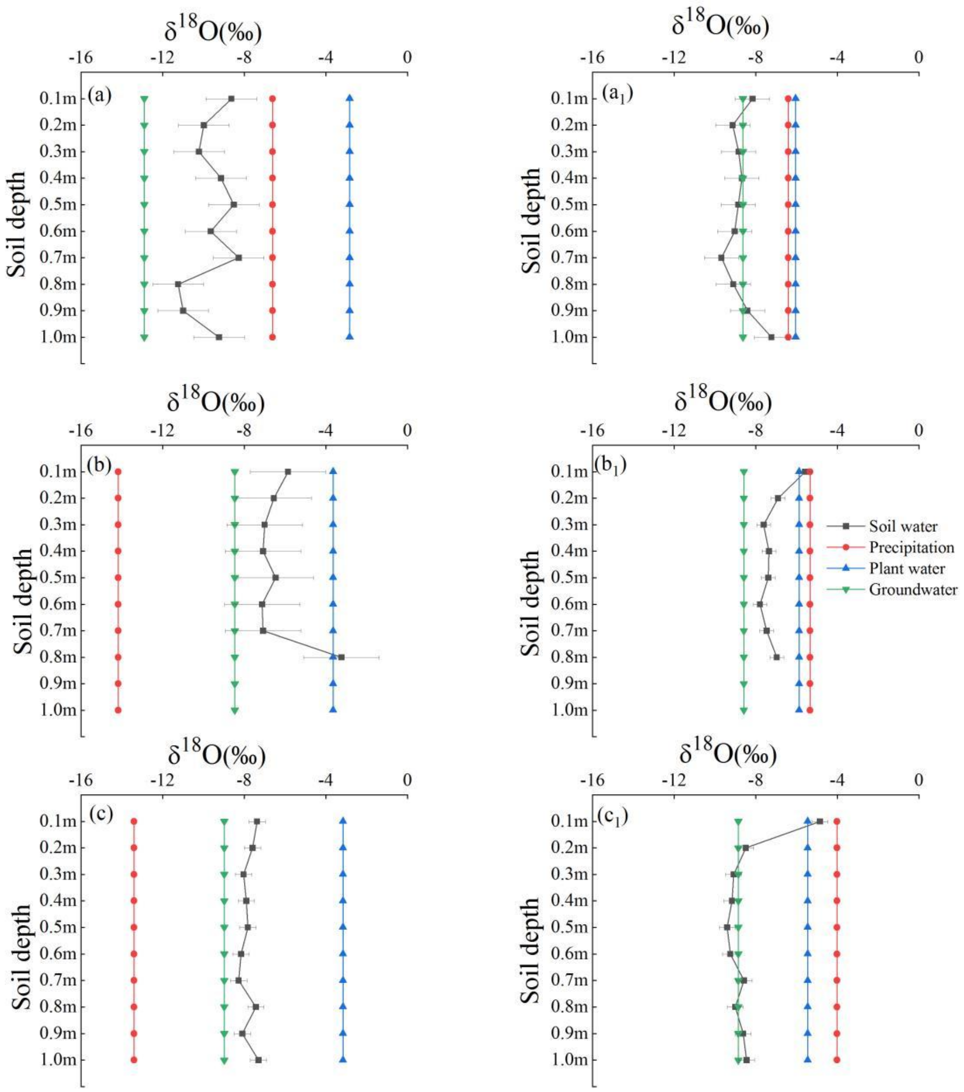

Fig. 4 (a)-(c) represents the variation of $\delta^{18}O$ of soil, plant, precipitation and groundwater with soil depth in the alpine meadow, forests and arid foothills in the dry season, and (a_1)-(d_1) represents the variation of $\delta^{18}O$ of soil, plant, precipitation and groundwater in the alpine meadow, forests and arid foothills in the rainy season

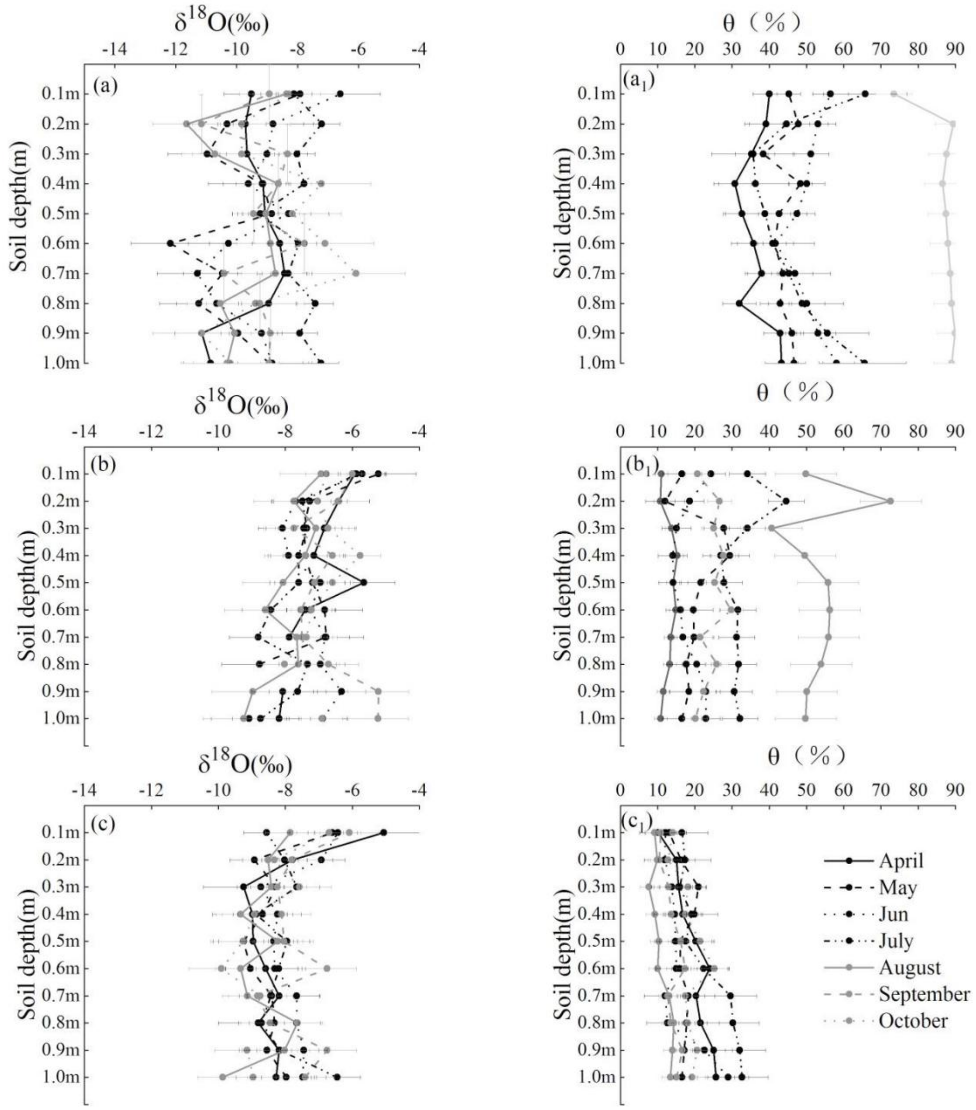

Fig.5 The variation of $\delta^{18}O$ and soil water content (θ, %) with soil depth. (a)-(c) represent alpine meadow, forests and arid foothills, respectively

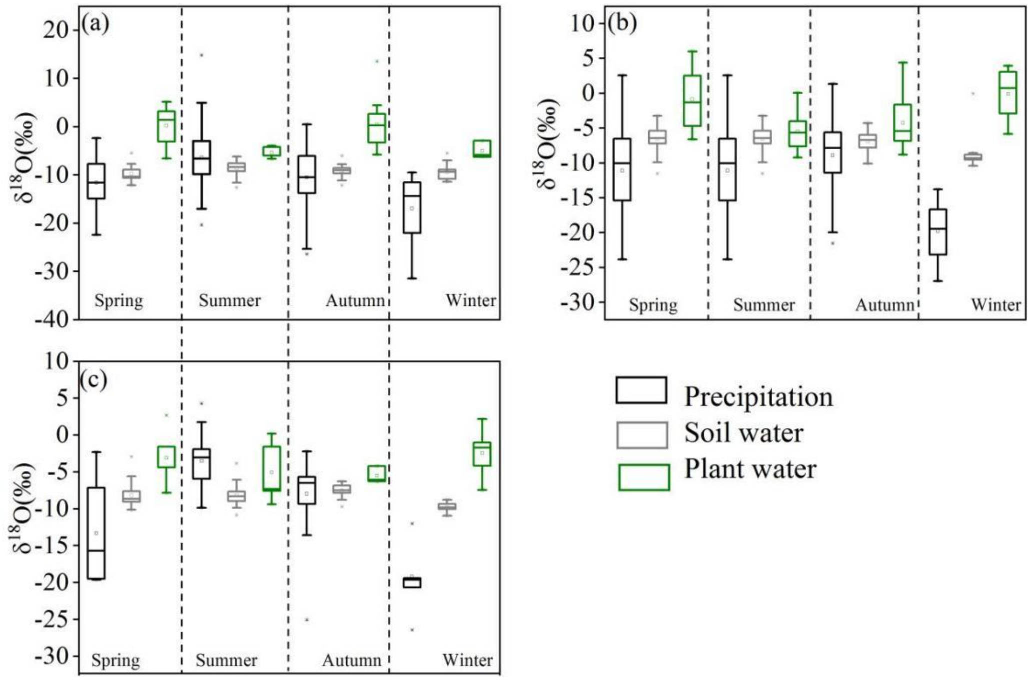

Fig. 6 Seasonal variations of different water isotopes in alpine meadow (a), forests (b) and arid foothills (c)

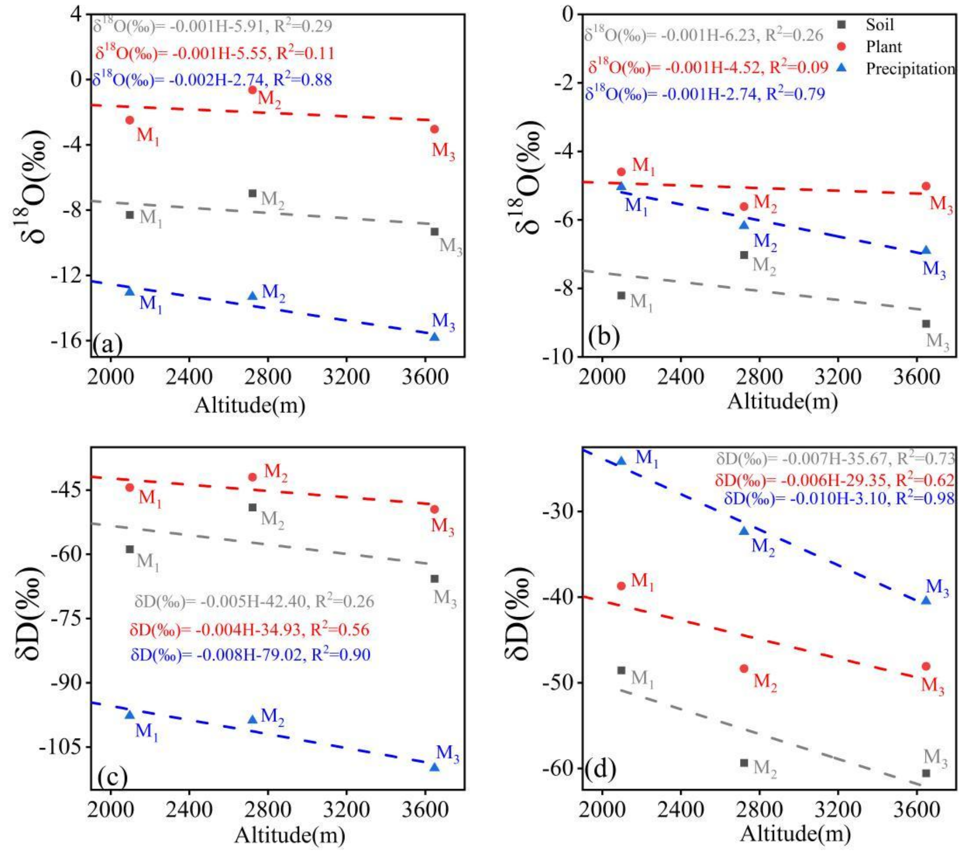

Fig. 7 Relationship between different isotope and altitude in the dry season (a, c) and in the rain season (b, d), M_1 stands for alpine meadows, M_2 stands for forests, and M_3 stands for arid foothills

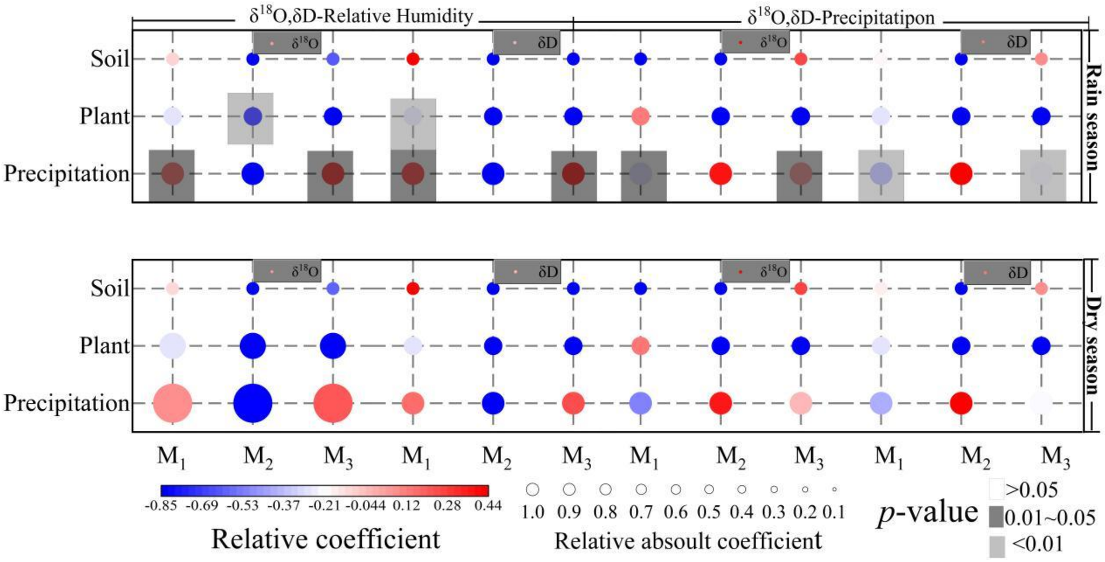

Fig. 8 Relationship between different isotope and relative humidity and precipitation, M_1 stands for alpine meadows, M_2 stands for forests, and M_3 stands for arid foothills

Table 1 Basic information table of sampling points

Sampling Station		Geographical Parameters			Meteorological Parameters	
		Longitude (E)	Latitude (N)	Altitude (m)	Average annual temperature (°C)	Average annual precipitation (mm)
M1	Lenglong	101°50'	37°33'	3647	-0.20	595.10
M2	Hulin	101°53'	37°41'	2721	3.24	469.44
M3	Xiying	102°18'	38°29'	2097	7.99	194.67

Table 2 Comparison of stable isotope of water in different vegetation zones

Vegetation zone types	Water types	$\delta^{18}O$(‰)				δD(‰)			
		Min	Max	Average	Coefficient of Variation	Min	Max	Average	Coefficient of Variation
Alpine meadow	Precipitation	-31.49	14.79	-9.44	-0.70	-238.62	63.43	-59.43	-0.84
	Soil water	-12.62	-5.46	-9.16	-0.16	-83.86	-26.13	-62.92	-0.16
	Plant water	-6.68	5.12	-1.68	-2.18	-60.22	-12.14	-41.14	-0.28
	Groundwater	-10.07	-7.71	-8.84	-0.07	-68.55	43.72	-54.85	-0.10
Forest	Precipitation	-26.96	4.38	-8.63	-0.74	-205.40	41.35	-60.24	-0.87
	Soil water	-11.96	-0.07	-7.01	-0.25	-78.43	-18.48	-48.68	-0.21
	Plant water	-9.24	5.98	-5.44	-1.31	-63.29	-23.77	-45.12	-0.24
	Groundwater	-10.25	-7.43	-8.56	-0.09	-68.80	-43.75	-53.46	-0.12
Arid foothills	Precipitation	-26.47	4.24	-7.50	-0.87	-194.34	38.62	-48.62	-1.04
	Soil water	-10.98	-2.96	-8.23	-0.15	-74.22	-8.79	-59.17	-0.12
	Plant water	-9.41	2.67	-3.61	-0.88	-74.90	-29.39	-48.79	-0.23
	Groundwater	-10.34	-7.43	-8.88	-0.07	-71.67	-44.26	-55.12	-0.09

Table 3 Correlation between precipitation isotopes and different temperatures in different vegetation zones

Vegetation zone type	Correlation below 0°C ($\delta^{18}O$ /δD)	Correlation between 0°C-8°C ($\delta^{18}O$ /δD)	Correlation above 8°C ($\delta^{18}O$ /δD)	Correlation during the study period
Alpine meadow	0.51*/0.59*	0.30*/0.24*	0.15/0.12	0.59*/0.61*
Forest	0.95*/0.94*	0.66*/0.69*	0.14/0.10	0.69*/0.65*
Arid foothills	0.47/0.51	0.79*/0.71*	0.31/0.14	0.83*/0.81*

Table 4 Correlation between different isotopes' $\delta^{18}O$ and relative humidity and precipitation in different vegetation zones

Meteorological parameters	Isotope types	Rain season			Dry season		
		Alpine meadow	Forest	Arid foothills	Alpine meadow	Forest	Arid foothills
Relative Humidity	Soil	y= -0.001x-8.89, R^2=0.001	y= -0.03x-5.21, R^2=0.13	y= -0.002x-8.01, R^2=0.002	y= -0.01x-8.39, R^2=0.03	y= 0.01x-7.21, R^2=0.07	y= -0.04x-6.38. R^2=0.38
	Plant	y= -0.11x+6.11, R^2=0.11	y= 0.08x-10.53, R^2=0.13	y= 0.05x-7.68, R^2=0.04	y= -0.09x+3.78, R^2=0.10	y= -0.02x-0.28, R^2=0.004	-
	Precipitation	y= -0.22x+9.45, R^2=0.28	y= 0.02x-9.50, R^2=0.002	y= 0.13x+3.57, R^2=0.29	y= 0.02x-16.47, R^2=0.002	y= 0.16x+4.33, R^2=0.72	y=0.08x-20.23, R^2=0.02
precipitation	Soil	y= 0.04x-9.55, R^2=0.15	y= 0.02x-7.36, R^2=0.01	-	y= -0.13x-8.94, R^2=0.18	-	y= 0.06x-8.73, R^2=0.06
	Plant	y -0.07x-1.09, R^2=0.002	y= -0.06x-5.01, R^2=0.01	y= 0.18x-6.00, R^2=0.05	y= 0.07x-2.75, R^2=0.03	y= -0.41x-0.32, R^2=0.06	-
	Precipitation	y= -0.30x-5.21, R^2=0.09	y= -0.17x-6.17, R^2=0.05	y= -0.28x-2.84, R^2=0.14	y= -0.14x-14.24, R^2=0.002	y= 0.17x-9.41 R^2=0.11	y=0.14x-16.49, R^2=0.02